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PHYSICS DEPARTMENT

Linfield College
McMinnville, Oregon

FIELD EMISSION RESEARCH
STATUS REPORT

1 JANUARY 1953 - 1 APRIL 1953

PROJECT N6onr - 72401 AUTHORITY NR 07/ - 171

8 April 1953

Physics Department

TO: Office of Naval Research
Department of the Navy
1000 Geary Street
San Francisco 9, California

FROM: W. P. Dyke
Head, Physics Department
Linfield College
McMinnville, Oregon

SUBJECT: Quarterly Status Report, Project N8-onr-72401
Period from 1 January 1953 to 1 April 1953.

The work under subject contract during subject period has concerned a further study of phenomena accompanying the field emission of very large current densities. This work has included the completion of a comparison between experiment and theoretical study concerning the effects of space charge on field emission. A new theoretical treatment of the emission of electrons from metal in the presence of high temperatures and high electric fields has been completed. A comparison between that theory and new experiments is well along towards completion. Two additional publications have been submitted concerning the field emission initiated vacuum arc between metal electrodes in high vacuum. Other publications are in progress. Dr. W. W. Dolan of the Mathematics Department of the College has replaced Mr. Barney on the project payroll for the time being in order to expedite the foregoing theoretical studies.

1. PUBLICATIONS.

The paper "Field Emission: Large Current Densities, Space Charge, and the Vacuum Arc" by Dyke and Trolan appeared in the 15 February 1953 Physical Review. Reprints are available and covers are being prepared in order to circulate these reprints to the subject project distribution list as Technical Report #2.

The paper "The Field Emitter: Microscopy, Fabrication and Electric Field Calculations" by Dyke, Trolan, Dolan and Barnes, is scheduled for publication in the May issue of the Journal of Applied Physics.

The papers "On the Field Emission Initiated Vacuum Arc", Part I by Dyke, Trolan, Martin and Barbour, and Part II by Dolan, Dyke and Trolan have been submitted for publication in the Physical Review.

At low voltage the positive terms of Eq. (1) are negligible, and the relation reduces to $V = F_0 x$, the expected form in the absence of space charge. At sufficiently high V, the negative terms are negligible, and the equation reduces to an equivalent of Child's equation:

$$J = (4/9kx^2)\, V^{3/2} , \qquad (2)$$

which is well known in thermionic emission. At intermediate voltages solutions of Eq. (1) may be obtained by numerical approximation, and the results plotted in terms of log J vs. $10^8/F$ for comparison with the Fowler-Nordheim characteristic. Such a comparison appears in Figure 1. In the figure, AE is the expected Fowler-Nordheim line without space charge; BD is a graph of Child's equation (2); ACD is the graph of Eq. (1). In this calculation the value of x is so chosen that the surface field (space charge neglected) is equal to that encountered in a given experiment; this requires that $x = 1/\beta$ where β is the geometric factor defined by $F = \beta V$.

Figure 2 is a comparison of the experimental data already cited from a previous report (2), with the corresponding curves predicted by Eq. (1). The various work functions ø in Curves 1-4 correspond to different degrees of barium coating on the tungsten emitter. The experimental points have been re-plotted in terms of log J instead of log I by use of the emitting area as revealed through electron micrographs. Curve 5 is a graph of Child's equation for comparison.

Figure 3 is a series of plots using the present theory (Eq. 1) for work functions 4.35, 4.50, and 4.65 ev, corresponding respectively to accepted values for the (310) crystal face of tungsten, the average value in the neighborhood of 20 K.V. The value of β here used was that for Emitter Q-56. Emission pattern photographs of this emitter (not reproduced here) show that the usual dark areas characteristic of the weakly emitting (211) crystallographic direction disappeared at about 19 K.V., when the entire pattern was nearly uniform except for the central (110) spot, whose work function is thought to be 5.0 ev or higher. This observed "wash-out" of pattern detail is thus demonstrated to be consistent with the present theory.

As noted above, this work is in preparation for submission to the <u>Physical Review</u>. The adequacy of the present theory to account for the observed experimental results suggests that further work concerning the effects of space charge on the cold cathode field emission will not be required at this time. Project effort will instead be concentrated on problems described in the following sections.

3. THE EMISSION OF ELECTRONS FROM METAL AT HIGH TEMPERATURES AND HIGH FIELDS.

Previous reports and published papers (see reference 1, also paragraph 1 herewith) have pointed out experimental evidence that the normal field emission is appreciably increased when the emitter is resistively heated leading to electrical breakdown. Since the existing literature contains only scattered and partial theoretical treatments of emission under simultaneous high field and high temperature, an investigation of the problem has been undertaken here.

The general principles of such emission are well known. The current density J is given by an integral of the form

$$J = c \int_{-\infty}^{\infty} A(\epsilon)\, D(\epsilon)\, d\epsilon \; . \qquad (1)$$

Here c is a combination of physical constants; the variable ϵ is electron energy due to motion normal to the metal surface, measured from an origin at the top Fermi level. The function $A(\epsilon)$ represents the supply of electrons in the metal based on the Fermi-Dirac statistical distribution, and is a function of temperature T. $D(\epsilon)$ is the transmission coefficient or probability of penetration of the surface potential barrier; it is the function of surface electric field F but not of T. $D(\epsilon)$ has been variously calculated by several authors, whose results are not in serious disagreement. The form used here is that of Sommerfeld and Bethe, [4], and it should be pointed out that results depend on the assumption of a potential barrier compatible with theirs.

The product $A(\epsilon)\, D(\epsilon)$ is not readily integrated in the general case, though results for the extreme cases of high T and low F ("pure thermionic emission") and of high F and low T ("cold field emission") are well known. Numerical integration of the function in the general case, using Simpson's formula, has been used here with accuracy at least comparable with that of the corresponding experimental data. The predicted results for a variety of temperatures and fields, as applied to pure tungsten of work function $\phi = 4.50$ ev, are graphed in Figure 4. This figure compares favorably with the corresponding results of Guth and Mullin [5] over the restricted range possible by their method.

It is notable that the temperature effect is very great at fields near the lower limit of present experimental work, decreasing to an almost negligible effect at the upper limit of the range. Experiments are in progress for the verification of this theory; early results indicate general agreement

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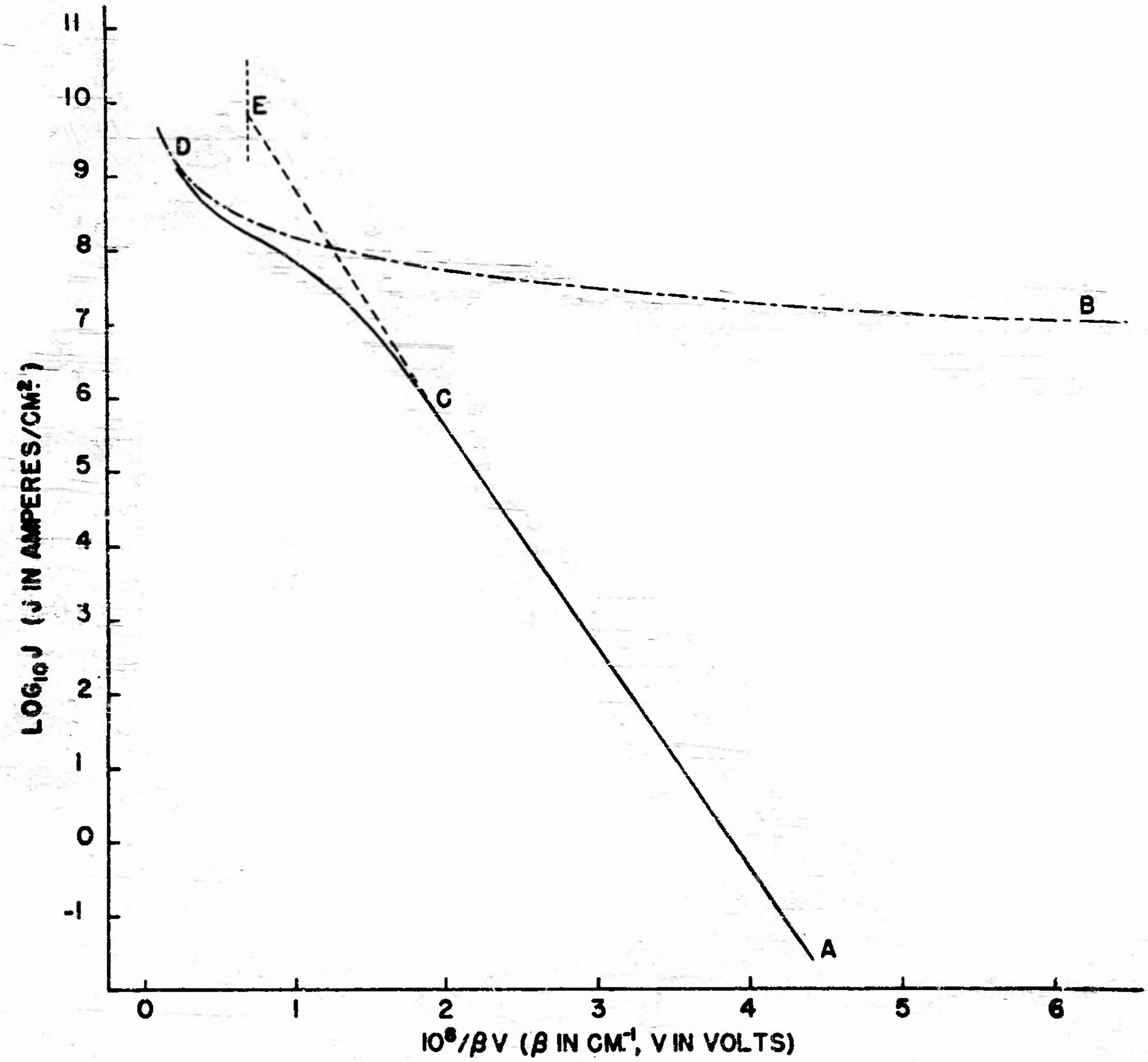
4. A. Sommerfeld and H. Bethe, Handbuch der Physik (J. Springer, Berlin, 1933), Vol. XXIV, No. 2, p. 441.
5. E. Guth and C. J. Mullin, Phys. Rev. 61, 339 (1942).

Incidental to the integration process, curves have been drawn for the energy distribution of the emitted electrons (the areas under these are proportional to current density). The curves are of interest in themselves as giving an accurate description of the shift of the energy level of maximum emission from near the Fermi level for low temperatures to the top of the potential barrier for high temperatures.

A considerable experimental program is needed to verify several aspects of this theory.

W. P. Dyke
Director of Research



11
10
9
8
7
6
5
4
3
2
1
0
-1
LOG10 J (J IN AMPERES/CM.²)
E
D
B
C
A
0
1
2
3
4
5
6
10⁸/βV (β IN CM.⁻¹, V IN VOLTS)

Figure 1

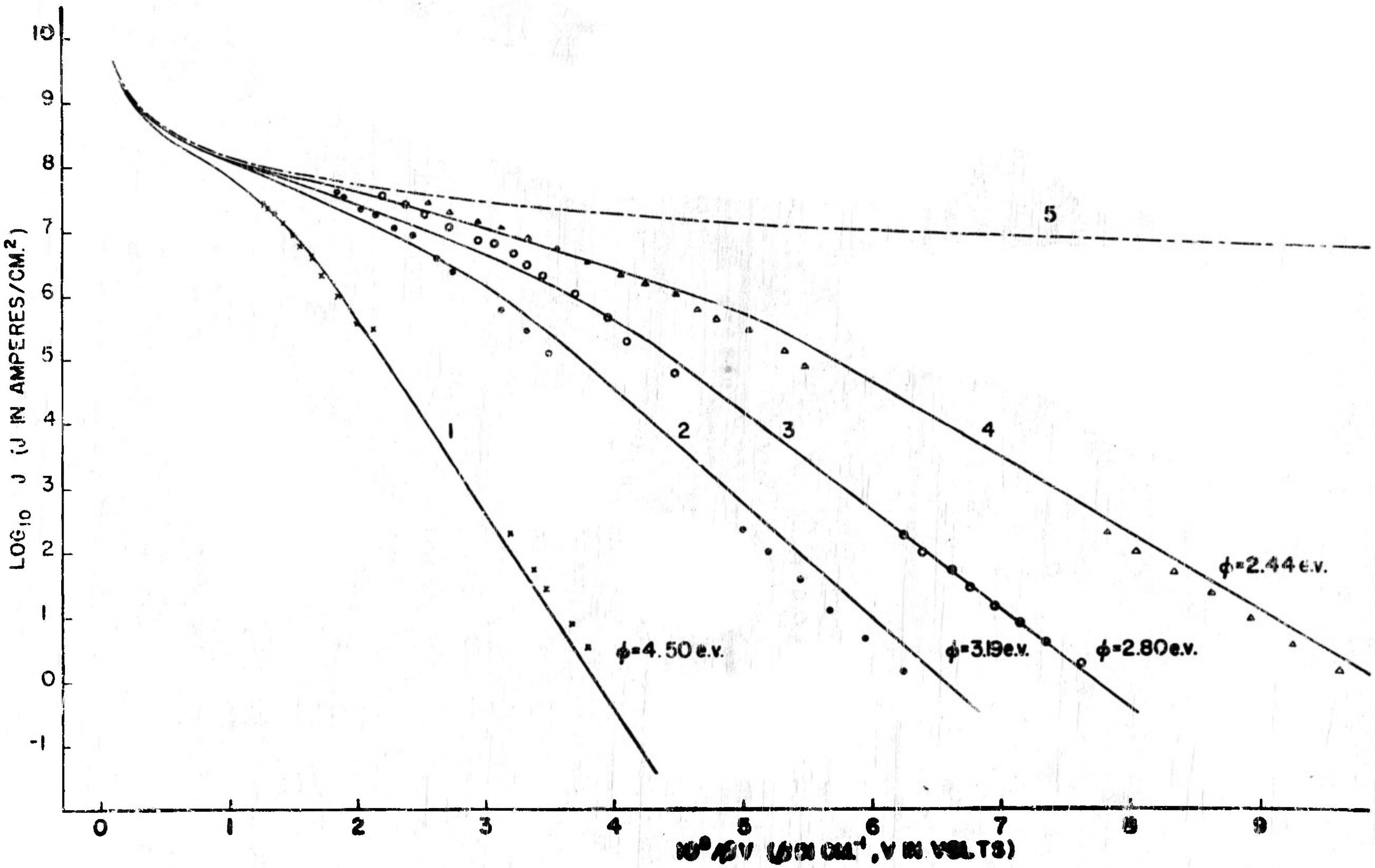
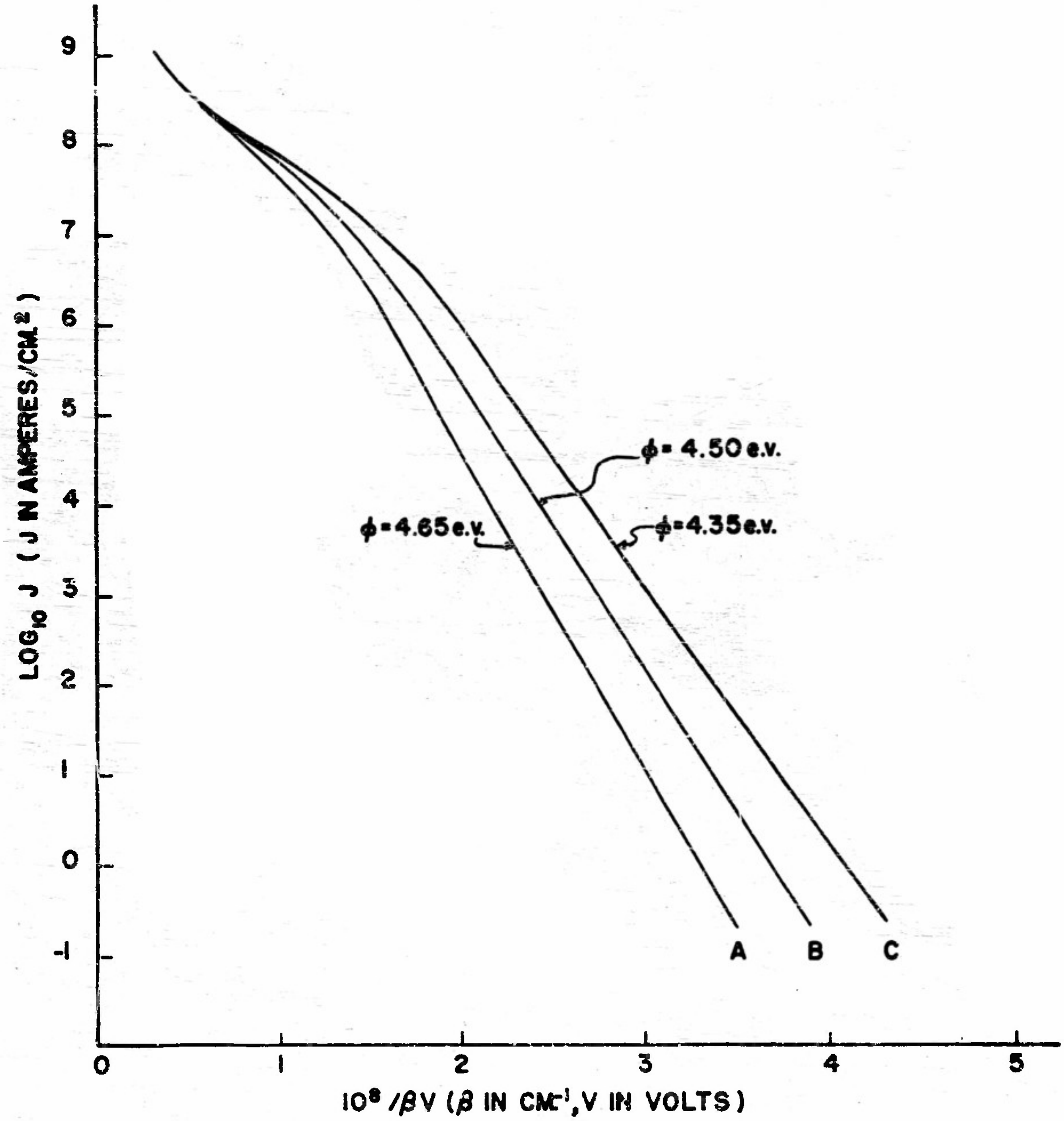
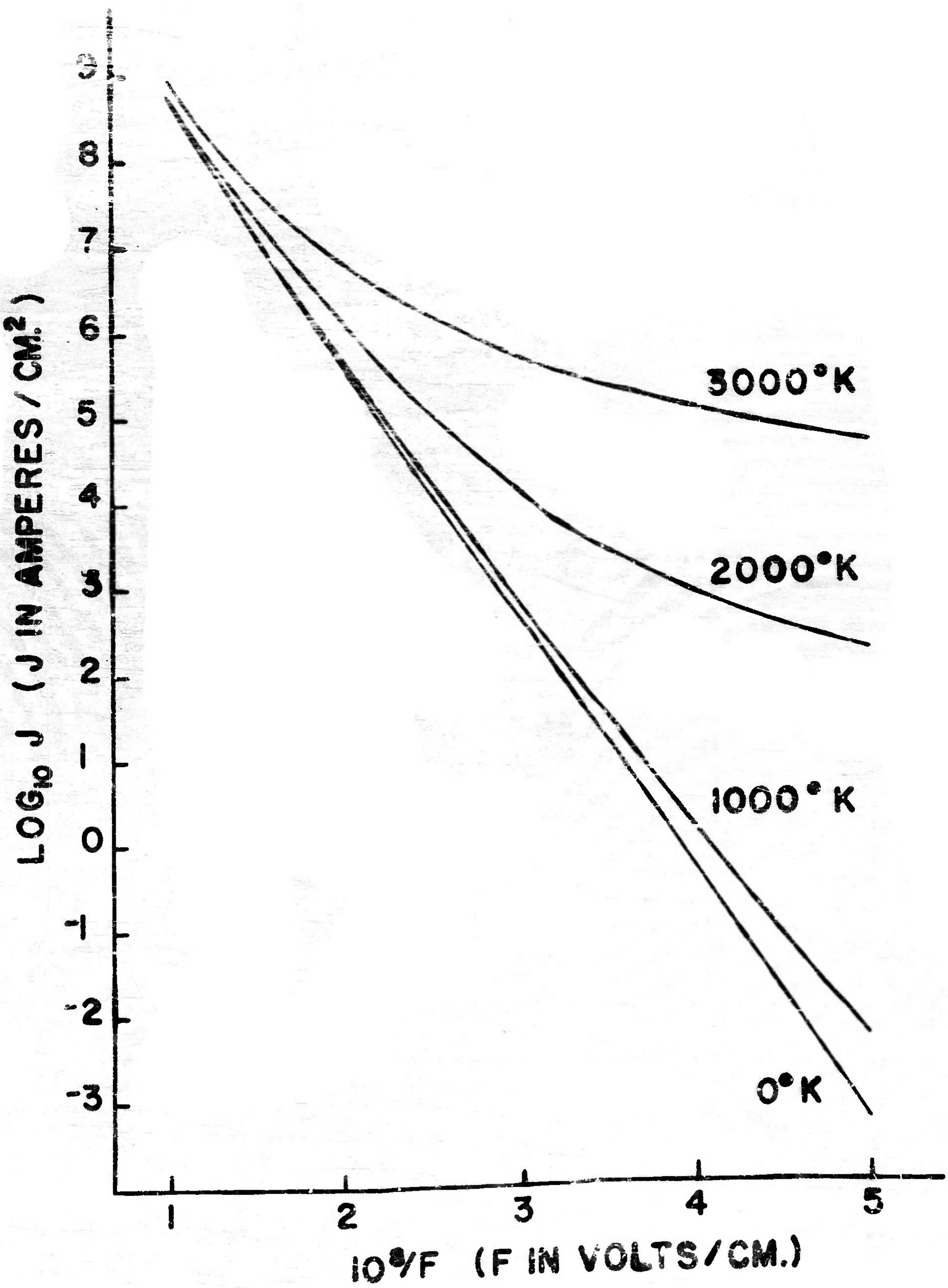


Figure 2



9
8
7
6
5
4
3
2
1
0
-1
LOG10 J (J IN AMPERES/CM.2)
0
1
2
3
4
5
10⁸ /βV (β IN CM⁻¹, V IN VOLTS)
φ= 4.50 e.v.
φ=4.65 e.v.
φ=4.35 e.v.
A
B
C

Figure 3



LOG10 J (J IN AMPERES / CM.2)
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
3000°K
2000°K
1000°K
0°K
1
2
3
4
5
10⁸/F (F IN VOLTS/CM.)

Figure 4